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FIRST & SECOND QUARTER PROGRESS
REPORT 1987 ON PLASMA THEORY
AND SIMULATION

January 1 to June 30, 1987

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ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley, CA 94720

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Our group uses theory and simulation as tools in order to increase the understanding of plasma instabilities, heating, transport, plasma-wall interactions, and large potentials in plasmas. We also work on the improvement of simulation both theoretically and practically.

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Research in plasma theory and simulation, plasma-wall interactions, large potentials in plasmas.

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

See reverse side

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20. ABSTRACT

General Plasma Theory and Simulation

A. Ion acceleration in the plasma source sheath, with an initial ion velocity. It is found analytically that ions leave the source with drift velocity greater than v_{sound} obviating the need for pre-sheath acceleration in the bulk plasma, preceding a collector sheath.

Plasma Wall Physics, Theory and Simulation

* A. Collector and source sheaths of a finite ion temperature plasma; abstract provided.

* B. Effects of secondary electron emission on the collector and source sheaths of a finite ion temperature plasma; abstract provided.

* C. Effects of ion reflection on the collector and source sheaths of a finite ion temperature plasma; abstract provided.

*,** D. Vortex dynamics and transport to the wall in a crossed field plasma sheath; abstract provided.

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FIRST AND SECOND QUARTER PROGRESS REPORT
ON
PLASMA THEORY AND SIMULATION

January 1 to June 30, 1987

Our research group uses both theory and simulation as tools in order to increase the understanding of instabilities, heating, transport, plasma-wall interactions, and large potentials in plasmas. We also work on the improvement of simulation, both theoretically and practically.

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June 30, 1987

ELECTRONICS RESEARCH LABORATORY

University of California
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SECTION I: GENERAL PLASMA THEORY AND SIMULATION

ION ACCELERATION IN THE PLASMA SOURCE SHEATH,

WITH AN INITIAL ION VELOCITY

C.K. Birdsall and S. Kuhn[†]

In an earlier note,[1] we used a plasma source sheath and found a number of useful results, for a monotonically decreasing potential, such as the ion velocity at the plasma equalling or exceeding the ion sound velocity (hence, obviating the need for a Bohm pre-sheath field - or simply placing such at the source), and a maximum value for the ion flux into plasma.

In this note, we will still approximate the ions by a cold beam but now add an initial ion velocity, in order to get around the dilemma of infinite ion density and zero ion velocity at the source. See Fig. 1 for the model. Assuming that most electrons are reflected to the source, the electron density is still given by a Boltzmann factor, with coefficient of $n_{eo} \cong 2n_{eo}^{+}$, where the + means that injected in the $+x$ direction. The ion flux density is given by, independent of dimension x,

$$\Gamma_i = n_i(x)\, v_i(x) = n_{io}^{+} \left[\sqrt{\frac{2}{\pi}}\, v_{tio} \right] \tag{1}$$

We take the ion initial velocity to be given by

$$v_{io} = \sqrt{\frac{2}{\pi}}\, v_{tio} \tag{2}$$

where

$$v^2_{tio} = \frac{KT_{io}}{M}$$

Hence, the ion density is given by

$$n_i(x) = \frac{\Gamma_i}{v_i(x)} = n_{io}^{+} \sqrt{\frac{2}{\pi}}\, \frac{v_{tio}}{v_i(x)} = n_{io}^{+} \sqrt{\frac{2}{\pi}}\, \frac{v_{tio}}{\sqrt{\frac{-2e\,\Phi(x)}{M} + v_{io}^2}} \tag{3}$$

The problem now is to solve Poisson's equation, in one dimension,

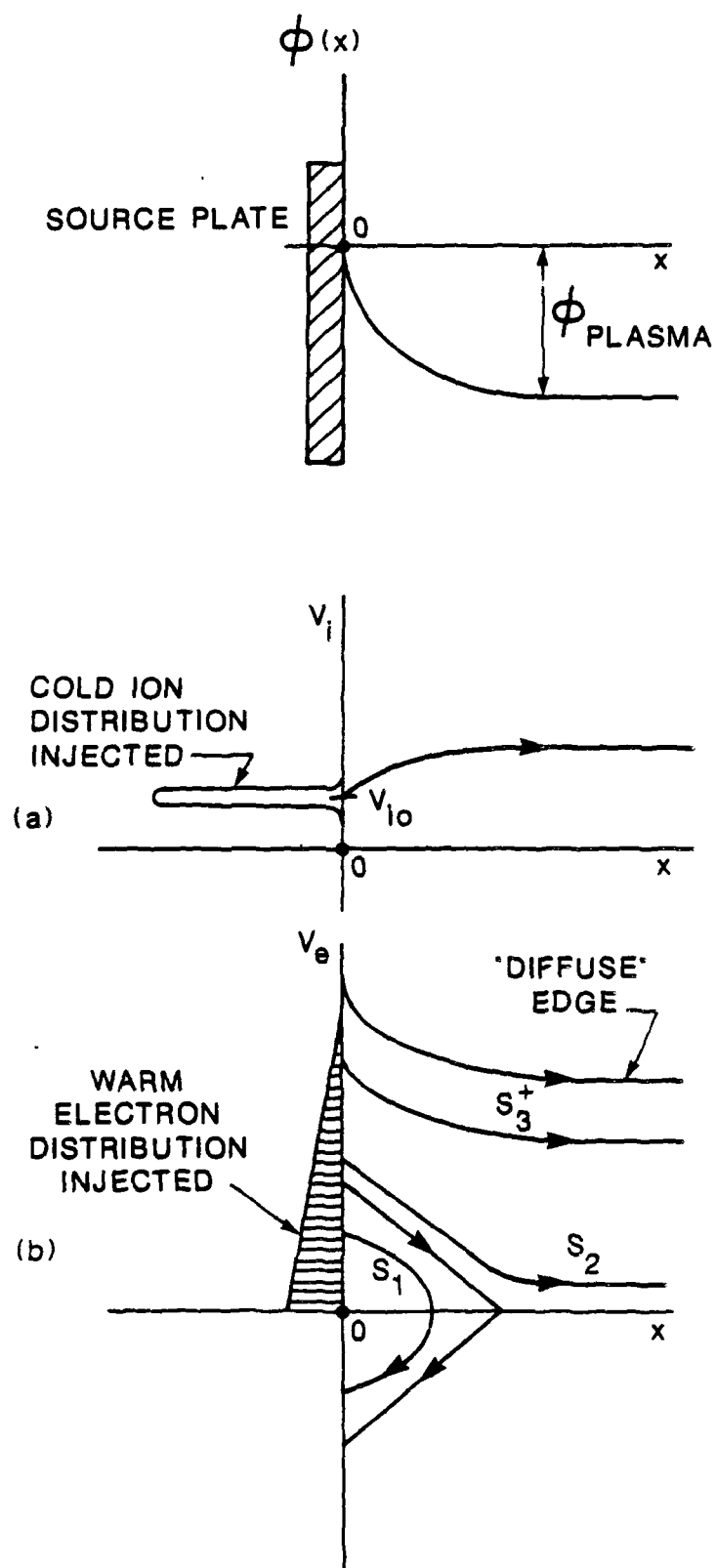[†]Frequent guest, from Institut für Theoretische Physik, Universität Innsbruck, Innsbruck, Austria.

Figure 1. Model for planar source sheath, with warm electrons injected, along with cold ions injected at initial velocity v_{io}.

$$\frac{d^2\Phi(x)}{dx^2} = -\frac{\rho}{\varepsilon_o} = -\frac{e}{\varepsilon_o}\ (n_i(x) - n_e(x)) \tag{4}$$

We will use the normalized variables

$$\eta \equiv \frac{e\phi}{kT_e},\ \xi \equiv \frac{x}{\lambda_{Deo}},\ \alpha \equiv \frac{n_{io}^+}{n_{oe}^+},\ \tau_o = \frac{T_{io}}{T_{eo}} \tag{5}$$

where $\lambda_{Deo} = \sqrt{\varepsilon_0\, kT_{eo}/(2n_{eo}^+\, e^2)}$. Thus, Poisson's equation now is

$$\eta''(\xi) = \frac{-\alpha}{2\sqrt{1 - \frac{\pi\eta(\xi)}{\tau_o}}} + e^{\eta(\xi)}. \tag{6}$$

The variables η and α ("neuralization parameter", "injection ion richness") are those of Kuhn (1981),[2] whereas his normalized distance was $\xi' = x/\lambda_{Deo}^+$, with $\lambda_{Deo}^+ = \sqrt{\varepsilon_0\, kT_{eo}/(n_{eo}^+\, e^2)}$. Kuhn[2] did the complete numerical solution for the case $\tau_0 = 1$, for which we will find simple analytic results.

(In the previous note,[1] the initial ion velocity was zero, just as it was in the derivation of the famous Child's Law of 1911;[3] the physics is that the initial ion velocity is much smaller than the directed ion velocity in most places elsewhere. We avoid the zero here, with an initial ion velocity equalling the average velocity of a half Maxwellian at temperature T_{io}.)

Our object is to solve Poisson's equation so as to obtain the potential at the inflection point (where $\eta'' = 0$), which we take to be the plasma potential, η_p, as done by Kuhn[2] and others. This solution is from (6), as

$$\alpha = 2\, e^{\eta_p} \sqrt{1 - \frac{\pi\eta_p}{\tau_o}} \qquad (\eta_p < 0) \tag{7}$$

This expression gives us the normalized ion density at the source (i.e., the neutralization parameter α) which we take to be the maximum ion density in this system.

We now can plot the plasma potential η_p in terms of the injected ion richness, α, as done by Kuhn[2] (numerically) in his Figure 2(a), for large negative collector bias. We plot our results on top of his figure and find excellent agreement for the plasma potential up to ion richness factor $\alpha \cong 2$. Our result (7) has a maximum ion richness value of $\alpha = 2.09$ at a potential of $\eta_p = -0.18$. Some numbers of
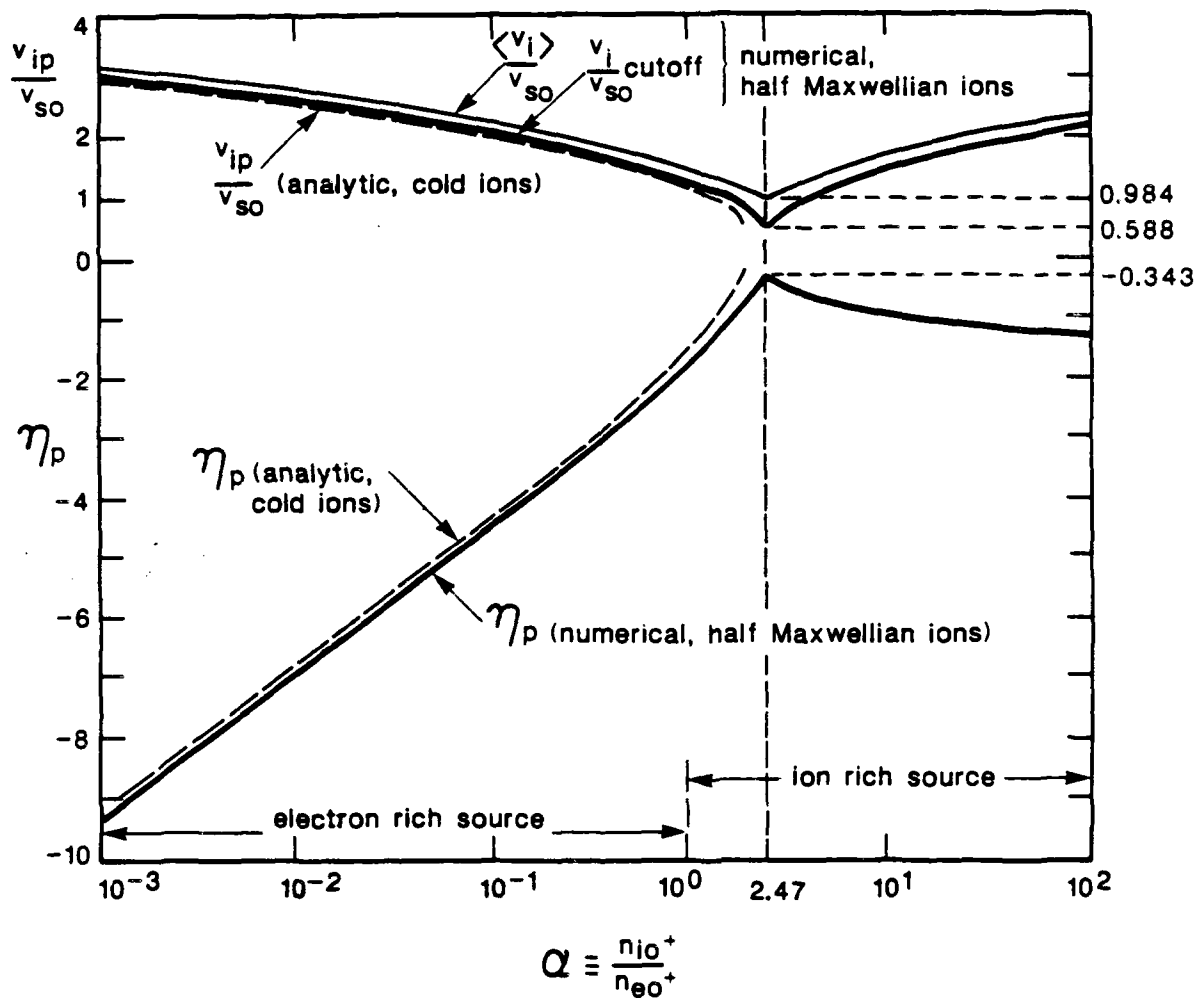
Figure 2. Plasma potential η_p, mean ion velocity $<v_i>$ and slowest ion velocity $v_{icutoff}$ at the plasma edge as a function of ion richness, α; numerical results taken from $Kuhn$[2]. The dashed lines show the analytic results of this note, really overlaying Kuhn's results, up to $\alpha \approx 2$.

interest are:

at $\alpha = 1.0$, $\eta_p = -1.58$, $\dfrac{v_{ip}}{v_{so}} = 1.38$, with v_{so} defined below

Let us now look at the ion speed at the "plasma", defined as above. The ion speed in the plasma region comes from

$$v_i^2 = \frac{-2e\,\Phi}{M} + v_{io}^2 = -2\eta_p\frac{KT_{eo}}{M} + \frac{2}{\pi}\frac{KT_{io}}{M} \tag{9}$$

Let us define "sound speed" as

$$v_{so}^2 = \frac{K(T_{eo} + T_{io})}{M}$$

so that

$$\frac{v_i^2}{v_{so}^2} = \frac{2\,(\tau_o - \pi\eta_p)}{\pi(\tau_o + 1)} \tag{10}$$

For Kuhn's figure, the ions and electrons have equal temperatures at the source, $\tau_o = 1$, so that $v_{so} = \sqrt{2kT_{eo}/M}$ and the ion speed in the plasma region is found to be

$$\frac{v_{ip}}{v_{so}} = \sqrt{\frac{1}{\pi} - \eta_p} \tag{11}$$

where η_p is obtained from (7). This value is also plotted on top of Kuhn's results and is observed to be very close to his cutoff velocity (lowest ion velocity), and a l.tle lower than his average velocity.

The point is that in our cold-ion model

$$v_{i,\,plasma} > v_{sound,o}$$

for

$$\alpha \equiv \frac{n_{io}^+}{n_{eo}^+} \leq 2.$$

In the warm-ion model, the inequality $<v_i>_{plasma} > v_{sound}$, holds true for *almost all* values of α, as can be seen from Fig. 2. Hence, the ions are at least at sound speed upon leaving the planar source sheath, obviating the need for further Bohm acceleration in the (collsionless) plasma, preceding a collector sheath.

References

1. Previous QPR, 3 and 4, 1986

2. S. Kuhn, "Axial Equilibria, Disruptive Effects and Buneman Instability in Collisionless Single Ended Q Machines," *Plasma Physics* 23 (881-902) 1981

3. C. D. Child, "Discharge from Hot CaO," *Phys. Rev.*, Ser. I, 32, pp. 492-511.

SECTION II: PLASMA-WALL PHYSICS, THEORY AND SIMULATION

A. **Collector and Source Sheaths of a Finite Ion Temperature Plasma**
   L. A. Schwager and C. K. Birdsall

B. **Effects of Secondary Electron Emission on the Collector and Source Sheaths of a Finite Ion Temperature Plasma**
   L. A. Schwager

C. **Effects of Ion Reflection on the Collector and Source Sheaths of a Finite Ion Temperature Plasma**
   L. A. Schwager

   Three titles and abstracts follow. These will be ERL reports, soon.

D. **Vortex Dynamics and Transport to the Wall in a Crossed-Field Plasma Sheath**
   Kim Theilhaber and C. K. Birdsall

   An interim report has been issued (ERL Memo UCB/ERL M87/18 10 April 1987) in this area, with title and abstract following.

Collector and Source Sheaths of a Finite Ion Temperature Plasma

L. A. Schwager and C. K. Lirdsall

Abstract

The region between a Maxwellian plasma source and an absorbing surface is modeled with an electrostatic particle simulation and with a kinetic plasma-sheath model. In the kinetic model, Poisson's equation and Vlasov equations govern the velocity distribution of the ions and electrons. Our numerical and theoretical results for collector potential and plasma transport agree with the bounded model of Emmert *et al.* but differ somewhat from those using traditional Bohm sheath analysis. The plasma source injects equal fluxes of half-Maxwellian ions and electrons with specified mass and temperature ratios and is assumed to have a zero electric field. Representing the potential change within a distributed full-Maxwellian source region, the source potential drop depends primarily on temperature ratio and evolves a few Debye lengths from the source to neutralize the injected plasma. The plasma flows to an electrically floating collector where the more familiar electron-repelling collector sheath appears. Profiles of potential, density, drift velocity, temperature, kinetic energy flux, and heat flux are shown from simulation; all compare very well with theory.

Effects of Secondary Electron Emission on the Collector and Source Sheaths of a Finite Ion Temperature Plasma

L. A. Schwager

Abstract

The region between a Maxwellian plasma source and an absorbing surface which emits cool secondary electrons is modeled numerically with dynamic, electrostatic particle simulation and theoretically with a static, kinetic plasma-sheath model. The coefficient of secondary electron emission is varied up tc and beyond critical emission which causes electric field reversal at the collector. Results from these models agree very well over this wide range of emission coefficients. Increasing the secondary emission coefficient reduces the collector potential which increases the total energy flux to the collector while decreasing the ion energy deposited. In the simulation, some heating of the secondary electron stream is observed to gradually evolve over many Debye lengths, possibly because of a beam-plasma interaction. This heating increases potential fluctuations but causes only small deviations from the predictions with static theory.

Effects of Ion Reflection on the Collector and Source Sheaths of a Finite Ion Temperature Plasma

L. A. Schwager

Abstract

The region between a Maxwellian plasma source and an absorbing surface which reflects a fraction of the incident ions is modeled numerically with dynamic, electrostatic particle simulation and theoretically with a static, kinetic plasma-sheath model. The fraction ζ of ions reflected is varied from 0 to 0.6 which generally increases both the potential drop from the source to the collector and the energy transported to the collector surface. Results from both models agree well when the fraction reflected is less than 0.4 for full energy transfer to reflected ions. With larger fractions and with slightly less than full reflected energy, simulations show an ion-ion two-streaming interaction which slightly reduces the collector potential drop and decreases the ion energy deposited on the collector surface relative to predictions from the static theory. According to theory, for a deuterium-tritium plasma, a collector material causing the reflected ion fraction to be $\zeta = 0.2$ with full reflected energy increases the magnitude of collector potential by 12% and the ion energy deposited by 6% over those predicted when $\zeta = 0$.

Vortex Dynamics and Transport to the Wall in a Crossed-Field Plasma Sheath – K. Theilhaber and C.K. Birdsall.

Abstract

Results of numerical simulations of the time-dependent behavior of a transversely magnetized plasma-wall sheath are presented. These simulations have been conducted with the aim of modelling plasma behavior in the vicinity of the limiters and walls of a fusion device. The two-dimensional, bounded particle simulation code "ES2" has been used as a tool for the investigation of these edge effects, in an idealized geometry which retains, however, the essential features of the physics of the edge plasma. The simulations have revealed that the bounded plasma is subject to the so-called "Kelvin-Helmholtz" instability[1] an instability maintained by the non-uniform electric field which is induced by the presence of the material walls. This instability is seen to saturate into large and stable vortices, with $e\phi/T_i \sim 1$, which exist in the vicinity of the walls, and drift parallel to their surfaces. An important feature of these structures is that they continuously convect particles to the walls, at an "anomalous" rate much greater than that induced by collisional diffusion, a feature which seems tied to the mutual interaction of the vortices. In the code "ES2", volume ionization of neutrals has been modelled by a uniform electron-ion pair creation in the simulation region, and this results in a steady state, in which the linear edge instability, the nonlinear fluid dynamics of the vortices, and the nonlinear dynamics of the particles scattered by the vortices all balance each other. This steady-state but non-equilibrium configuration, which is a first model of the edge behavior induced by the boundaries, is conceptually analogous to Rayleigh-Bénard convection.

---

[1] S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, Oxford, at the Clarendon Press, 1961.

Reports

William S. Lawson, "Computer Simulation of Bounded Plasma Systems," University of California, Berkeley, Memorandum No. UCB/ERL M87/14, March 5, 1987. Submitted to *J. of Computational Physics*. Title changed to "Particle Simulation of Bounded 1-d Plasma Systems" after initial review.

K. Theilhaber and C. K. Birdsall, "Vortex Dynamics and Transport to the Wall in a Crossed-Field Plasma Sheath," University of California, Berkeley, Memorandum No. UCB/ERL M87/18, April 10, 1987.

Kim Theilhaber, "ES2 User's Manual--Version 1," University of California, Berkeley, Memorandum No. UCB/ERL M87/23, May 11, 1987.

R. J. Procassini, C. K. Birdsall, E. C. Morse, and B. I. "A Relativistic Monte Carlo Binary Collision Model for Use in Plasma Particle Simulation Codes," University of California, Berkeley, Memorandum No. UCB/ERL M87/24, May 14, 1987.

William S. Lawson, "Artificial Cooling Due to Quiet Injection in Bounded Plasma Particle Simulations," University of California, Berkeley, Memorandum No. UCB/ERL M87/34, May 21, 1987. Submitted to *J. of Computational Physics*.

Poster Papers

U.S./Japan Seminar: Effects of Electric Fields on Magnetic Confinement, January 22-24, 1987, University of California, Los Angeles:

K. S. Theilhaber and C. K. Birdsall, "Large Electric Fields in a Magnetized Plasma Sheath: Long-lived Vortices" (abstract follows)

Sherwood Controlled Fusion Theory Conference, San Diego, California, April 6-8, 1987 (abstracts follow):

K. Theilhaber, "Transport Induced by a Crossed-Field Sheath"

Richard J. Procassini, Charles K. Birdsall, Bruce I. Cohen, "Performance and Optimization of Direct Implicit Time Integration Schemes for Use in Electrostatic Particle Simulation Codes."

Lou Ann Schwager, "Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and Ion Reflection at the Bounding Surface"

IEEE International Conference on Plasma Science, Arlington, Va., June 1-3, 1987 (abstracts follow).

K. Theilhaber and C. K. Birdsall, "Large Electric Fields in a Magnetized Plasma Sheath; Long-lived Vortices"

L. A. Schwager and C. K. Birdsall, "Potential Drop and Transport in a Bounded Plasma Including Secondary Electron Emission and Ion Reflection at the Collector"

Visitor

Professor N. Sato, Tohoku University, Sendai, Japan; seminar, "Basic Experiments of Plasma Potential Formation in Magnetic Mirror Formation," January 24, 1987

Large Electric Fields in a Magnetized Plasma Sheath; Long-lived Vortices -

K. Theilhaber and C. K. Birdsall, University of California, Berkeley

We consider the equilibrium and time-dependent behavior of the plasma-wall sheath which is formed when the external magnetic field is parallel to the wall. The presence of the material boundary initially creates a layer of charge depletion near the surface, of thickness comparable to the ion gyro-radius. This results in a strongly nonuniform electric field which induces a sheared $\underline{E} X \underline{B}$ motion of ions and electrons parallel to the wall. Physical arguments as well as analytical and numerical studies suggest that this flow is subject to the Kelvin-Helmholtz instability, with a long-term evolution into a set of vortices separating the boundary from the plasma. We present an analytical model for the instability, and the results of two-dimensional, electrostatic particle simulations of this configuration, in the form of a movie, showing initialization of $\underline{E}$, the subsequent shear motion, and the buildup near the wall of vortices which live (at least) some 10's of ion gyroperiods.

Transport induced by a Crossed-Field Sheath[1] - K. THEILHABER,
Plasma Theory and Simulation Group, University of California, Berkeley,
CA 94720.

We are studying transport across the magnetic field in a plasma bounded
by conducting boundaries with the aim of modelling plasma behavior in the
vicinity of the limiters and walls of a fusion device. Our approach is to use
the two-dimensional, bounded particle simulation code "ES2" as a tool for
the investigation of edge effects, in an idealized geometry which retains,
however, the essential features of the physics of the edge plasma. Thus far,
our simulations have revealed that the bounded plasma is subject to the
so-called "Kelvin-Helmholtz" instability[2] an instability maintained by the
sheared electric field which is induced by the presence of the material walls.
This instability is seen to saturate into large and stable vortices, which can
be described by some variant of the so-called "Hasegawa-Mima" equations[3].
These vortices exist in the vicinity of the walls, and drift parallel to their
surfaces. An important feature of these structures is that they continuously
convect particles to the walls, at a rate much greater than that induced by
collisional diffusion. This property seems tied to the mutual interaction of
the vortices. In the code "ES2", we have modelled volume ionization of
neutrals by a uniform electron-ion pair creation in the simulation region,
and this results in a steady state, in which the linear edge instability, the
nonlinear fluid dynamics of the vortices, and the nonlinear dynamics of
the particles scattered by the vortices all balance each other. We consider
this configuration a first crude model of the edge behavior induced by the
boundaries. A movie will be shown, showing vortex formation and the
time-dependent depletion of the density profiles.

(a) $\omega_{ci}t = 5$ (b) $\omega_{ci}t = 55$ (c) $\omega_{ci}t = 305$
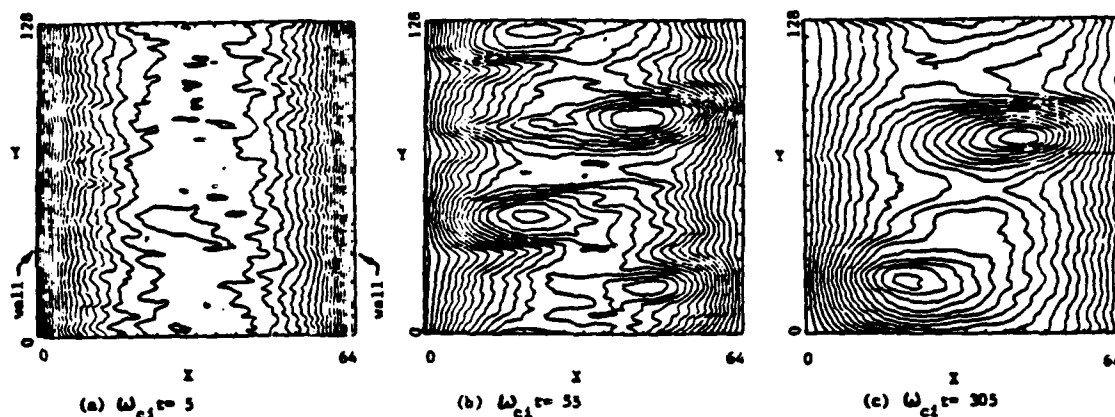
Equipotential contours for a bounded plasma simulation, at three different times.
The system was initially filled with a uniform electron-ion plasma, and left to evolve self-
consistently. 41000 particles of each species were initially in the system. The magnetic field
is rigorously perpendicular to the plane of the simulation, and the boundaries are conducting,
absolutely absorbing surfaces. The plasma parameters are such that, $m_i/m_e = 40$, $\omega_{pi}/\omega_{ci} = 2$,
$\omega_{pe}/\omega_{ce} = 0.3$, $\beta_e = 1.0$, $\lambda_{de} = \lambda_{di} = 3.3$, $\beta_i = 6.3$.
In the final state, the right-hand vortex is moving upward, the left-hand vortex downward. In
the presence of volume ionization, this final state is a steady-state, with electrons and ions
assuming triangular density profiles.

[1]This work supported by U.S. Department of Energy Contract No. FG03-86ER53220.
[2]S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, Oxford, at the Claren-
don Press, 1961.
[3]A. Hasegawa,K. Mima, Phys. Rev. Letters, **50**, 9, 28 February 1983, 682.

PERFORMANCE AND OPTIMIZATION OF DIRECT IMPLICIT TIME INTEGRATION SCHEMES FOR USE IN ELECTROSTATIC PARTICLE SIMULATION CODES*

Richard J. Procassini and Charles K. Birdsall
Electronics Research Laboratory
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and

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Lawrence Livermore National Laboratory
University of California
Livermore, CA. 94550

Implicit time integration schemes allow for the use of larger time steps than do conventional explicit methods, thereby extending the applicability of kinetic particle simulation methods. We will present the results of a study of the performance and optimization of two such schemes which are used to follow the trajectories of charged particles in an electrostatic, particle-in-cell plasma simulation code. The two direct implicit schemes, known as the C_1 and D_1 schemes, were chosen for their desirable properties which allow for the simulation of phenomena at frequencies much lower than the plasma or cyclotron frequencies. These properties include i) the relaxation of $\omega\Delta t$ constraints on the stability of the method, ii) strong damping of high-frequency modes for which $\omega\Delta t > 1$, and iii) second-order accuracy of the methods in the simulation of low-frequency phenomena for which $\omega\Delta t < 1$.

The formulation and optimization of the direct implicit schemes will be outlined, followed by a short discussion on the incorporation of these schemes into the electrostatic particle code. The results of a numerical stability study will also be presented. This study was based upon the freely expanding plasma slab model, which was run for various combinations of the important simulation parameters $\omega_{pe}\Delta t$, $\Delta x/\lambda_{De}$ in the range $0.1 \le \omega_{pe}\Delta t \le 200.0$, $0.1 \le \Delta x/\lambda_{De} \le 100.0$, excluding the region for which $v_e\Delta t/\Delta x > 2$. The degree of numerical heating or cooling (lack of energy conservation) was used as a quantitative measure of the numerical stability of the scheme. The results indicate that the D_1 scheme possesses a much larger region of parameter space over which energy is well conserved, than does the C_1 scheme. A locus of stable operating points is suggested by the data for each of the schemes.

Collector Sheath and Source Sheath in a Collisionless Finite Ion Temperature Plasma with Secondary Electron Emission and Ion Reflection at the Bounding Surface [1] - LOU ANN SCHWAGER, *Plasma Theory and Simulation Group, Electronics Research Lab, University of California, Berkeley CA 94720.*

For an electrically floating surface in contact with a plasma, our analytical and numerical results for the surface potential and plasma transport differ considerably from those using traditional Bohm sheath analysis. The finite sheath region between a collisional warm plasma and the confining, interacting surface is modeled numerically with electrostatic particle simulation using PDW1 and analytically with a plasma-sheath equation. The model and assumed boundary conditions along with a typical potential profile are shown below. For the purely absorbing surface, we derive the plasma-sheath equation for the boundary conditions shown below. The collisional plasma source can have arbitrary ion/electron ratios of mass and temperature. Our technique extends the analysis of Kuhn [2] with a temperature ratio $T_i/T_e = \tau = 1$ to include an arbitrary value for τ.

Simulation results after equilibration and our time-independent, analytic theory exactly agree. When compared with works such as that of Chodura [3] and Stangeby [4] who rely on a Bohm type of semi-infinite sheath model, our derivation predicts a lower wall potential ϕ_w for a mass ratio of 1836 and $\tau = 1$; this difference is within 20%. Our ϕ_w found with $\tau = 1$ and the ϕ_w derived by Stangeby and Chodura for $\tau = 0$ agree to within 2%. For $\tau \geq 1$ our results for the ion drift velocity v_D entering the collector sheath are within 4% of Stangeby's assumption that this velocity, normalized by the ion thermal velocity v_t is $(1 + \frac{1}{\tau})^{1/2}$. For $\tau \ll 1$ our results show a much smaller v_D; e.g. with $\tau = 0.1$ and a mass ratio of 1836, $v_D/v_t = 1.8$. Note that the presheath region, which we define below by ϕ_n, has a zero electric field; hence the "presheath acceleration" of the ions occurs entirely in the source sheath within a few Debye lengths lengths from the plasma source. Our potential results for a large range of mass and temperature ratios compare well with Emmert [5] who analytically models the plasma-sheath equation for a bounded system with Boltzmann electrons.

For electron-induced secondary electron emission, we have simulated emission beyond field reversal at the plate to emission coefficients Γ over 100%. For emission values up to the critical coefficient at field reversal, our dependence of ϕ_w on Γ for $\tau = 1$ compare well to that of Hobbs and Wesson [6] who assume $\tau \ll 1$. For the reflection of plasma ions, we have simulated reflection coefficients R up to 80%. The wall potential decreases as we increase R. Despite an ion-ion two-streaming interaction, which generates substantial potential fluctuations, the time-averaged values for ϕ_w and transport agree well with our time-independent analysis which assumes $\tau \ll 1$.
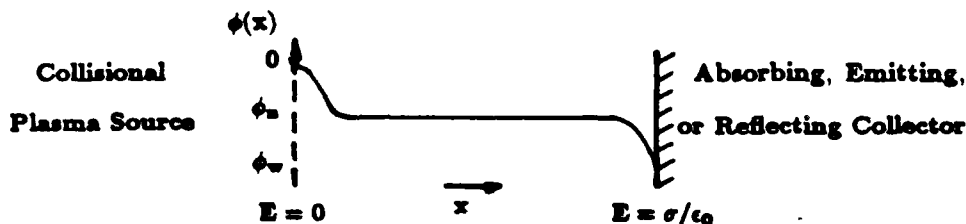
[2] S. Kuhn, *Plasma Physics* 23, 886 (1981).
[3] R. Chodura, *Journal of Nuclear Material* 111-112, 420 (1982).
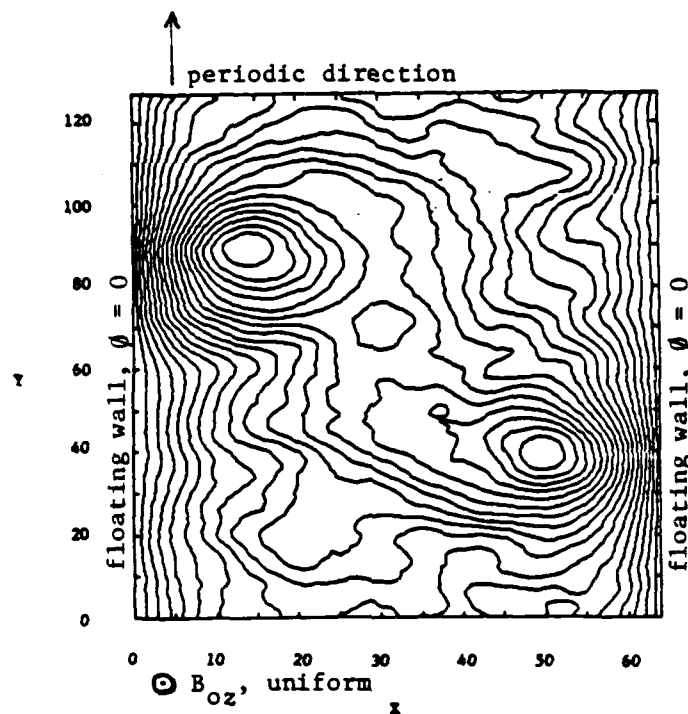[4] P. C. Stangeby, *Phys. Fluids* 27, 684 (1984).
[5] G. A. Emmert, *et al, Phys. Fluids* 23, 806 (1980).
[6] G. D. Hobbs and J. A. Wesson, *Plasma Physics* 9, 85 (1967).

Large Electric Fields in a Magnetized Plasma Sheath;
Long-lived Vortices - K. Theilhaber and C. K. Birdsall,
University of California, Berkeley, CA 94720

We consider the equilibrium and time-dependent
behavior of the plasma-wall sheath which is formed
when the external magnetic field is parallel to the
wall. The presence of the material boundary initially
creates a layer of charge depletion near the surface,
of thickness comparable to the ion gyro-radius. This
results in a strongly nonuniform electric field which
induces a sheared $\underline{E} \times \underline{B}$ motion of ions and electrons
parallel to the wall. Physical arguments as well as
analytical and numerical studies suggest that this
flow is subject to the Kelvin-Helmholtz instability,
with a long-term evolution into a set of vortices
separating the boundary from the plasma. We present
an analytical model for the instability, and the
results of two-dimensional, electrostatic particle
simulations of this configuration, in the form of a
movie, showing initialization of $\underline{E}$, the subsequent
shear motion, and the buildup near the wall of vortices
which live (at least) some 10's of ion gyroperiods.

Contour plot of the electrostatic
potential $\emptyset$ (x,y), at $\omega_{ci} t = 100$,
in a bounded plasma simulation, using
the code "ES2". The confining walls
are at x=0 and x=64, the external
magnetic field is perpendicular to
the plane of the simulation region.
The left-hand potential depression
is a vortex, streaming down the wall
with a velocity of about 0.1 v_{ti},
and the right-hand vortex is streaming
up the wall.

Potential Drop and Transport in a Bounded Plasma Including Secondary Electron Emission and Ion Reflection at the Collector[1]

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We simulate the model shown below numerically with electrostatic particle simulation using PDW1 and analytically with a plasma-sheath equation. Our numerical and analytical results for the surface potential and plasma transport differ considerably from those using traditional Bohm sheath analysis. For the purely absorbing surface, our analytic technique extends the analysis of Kuhn[2] with a temperature ratio $T_i/T_e = \tau = 1$ to include an arbitrary value for τ.

Simulation results after equilibration and our time-independent theory agree exactly for $\tau = 0.1$, 1.0, and 10.0. With PDW1 we observe that ϕ_w initially drops from 0 to 4-8 times the final equilibrated ϕ_w. The minimum ϕ_w occurs at 2-5 times the transit time of an ion with the mean velocity after the system is initialized. Note that the presheath region, which we define below by ϕ_n, has a zero electric field; hence the "presheath acceleration" of the ions occurs entirely in the source sheath within a few Debye lengths lengths from the plasma source. Our potential results for a large range of mass and temperature ratios compare well with Emmert[3] who analytically models the plasma-sheath equation for a bounded system with Boltzmann electrons.

When compared with works such as that of Chodura[4] and Stangeby[5] who rely on a Bohm type of semi-infinite sheath model, our derivation predicts a lower ϕ_w for a mass ratio of 1836 and $\tau = 1$; this difference is within 20%. Our ϕ_w found with $\tau = 1$ and the ϕ_w derived by Stangeby and Chodura for $\tau = 0$ agree to within 2%. For $\tau \geq 1$ our results for the ion drift velocity v_D entering the collector sheath are within 4% of Stangeby's assumption that this velocity, normalized by the ion thermal velocity v_t is $(1+\frac{1}{\tau})^{1/2}$. For $\tau \ll 1$ our results show a much smaller v_D; e.g. with $\tau = 0.1$ and a mass ratio of 1836, $v_D/v_t = 1.8$.

For electron-induced secondary electron emission, we have simulated emission beyond field reversal at the plate to emission coefficients Γ beyond 1. For emission values up to the critical coefficient at field reversal, our dependence of ϕ_w on Γ for $\tau = 1$ compare well to that of Hobbs and Wesson[6] who assume $\tau \ll 1$.

For the reflection of plasma ions, we have simulated reflection coefficients R up to 0.8. The wall potential decreases as we increase R. Despite an ion-ion two-streaming interaction, which generates substantial potential fluctuations, the time-averaged values for ϕ_w and transport agree well with our time-independent analysis which assumes $\tau \ll 1$.
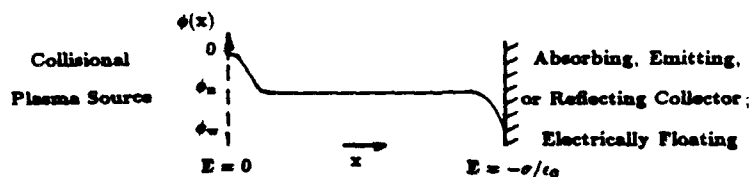
[1] This work supported by U.S. DOE Contract DE-FG03-86ER53220.

[2] S. Kuhn, *Plasma Physics* **23**, 886 (1981).

[3] G. A. Emmert, *et al*, *Phys. Fluids* **23**, 806 (1980).

[4] R. Chodura, *Journal of Nuclear Material* **111-112**, 420 (1982).

[5] P. C. Stangeby, *Phys. Fluids* **27**, 684 (1984).

[6] G. D. Hobbs and J. A. Wesson, *Plasma Physics* **9**, 85 (1967).

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